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INFLUENCE OF SILICON ON FRICTION AND WEAR OF IRON-COBALT ALLOYS

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16. Abstract <p>Sliding friction and wear experiments were conducted with ternary ordered alloys of iron and cobalt containing various amounts of silicon to 5 weight percent. The friction and wear of these alloys were compared to those for binary iron-cobalt alloys in the ordered and disordered states and to those for the conventionally used bearing material, 440-C. Environments in which experiments were conducted included air, argon, and 0.25 percent stearic acid in hexadecane. Results indicate that a ternary iron - cobalt - 5-percent-silicon alloy exhibits lower friction and wear than the simple binary iron-cobalt alloy. It exhibits lower wear than 440-C in all three environments. Friction was lower for the alloy in argon than in air. Auger analysis of the surface of the ternary alloy indicated segregation of silicon at the surface as a result of sliding.</p>					
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SUMMARY

An investigation was conducted to determine the influence of small additions (to 5 percent) of silicon on the friction and wear behavior of an ordered iron-cobalt alloy. Experiments were also conducted with the binary iron-cobalt alloy in the ordered and disordered states and with 440-C steel for comparative purposes. The environments for such studies included air, argon, and 0.25 percent stearic acid in hexadecane. Friction and wear were determined in pin on disk experiments.

The results of the investigation indicate that small amounts of silicon can reduce the friction and wear observed for the binary iron-cobalt alloy. Further, the ternary iron - cobalt - 5-weight-percent-silicon alloy exhibited lower wear than 440-C steel in all three environments and lower friction in argon. The friction for this ternary alloy was lower in argon than in air. The use of Auger analysis in a sliding friction experiment revealed surface segregation of silicon to the ternary alloy surface. This resulted from the sliding process and can account for large reductions in friction and wear with the additions of small amounts of silicon to the bulk alloy.

INTRODUCTION

Ordering in copper-gold and iron-cobalt alloys has been shown to influence friction and wear (refs. 1 and 2). In general, ordering in these alloys resulted in a decrease in both friction and wear. While ordering in the copper-gold alloy system is of fundamental interest, the iron-cobalt alloy system affords a greater opportunity for the use of ordered alloys in practical lubrication systems. Iron-base alloys are the most widely used materials in mechanical components.

In vacuum friction and wear studies in reference 2, the coefficient of friction for a 50-atomic-percent-iron - 50-atomic-percent-cobalt alloy in the ordered state was 3 percent of that obtained for the same alloy in the disordered state. Wear for the ordered structure was 6 percent of that for the disordered structure. This simple binary alloy in

the ordered state exhibited lower friction and wear in a vacuum than the conventionally used bearing material, 440-C steel.

While the binary iron-cobalt alloy had good friction and wear properties, this simple system is limited in mechanical properties. It would be desirable to have present in this alloy a third element which can alter mechanical properties (i.e., hardness) by such mechanisms as second-phase compound formation. An alloying element which can be used in this regard is silicon. Silicon has been present in many bearing materials, but the mechanism of its performance has not been adequately studied.

Silicon present in iron-cobalt alloys increases the order-to-disorder transformation temperature. With the addition of 5 percent silicon, the transformation temperature is increased by 170°C above the 732°C for the binary alloy (ref. 3). Further, silicon forms ordered structures with iron as well as compounds with cobalt (ref. 3). In addition, silicon affords the advantage of further reducing friction and wear (ref. 4). This could possibly result from the segregation of silicon to alloy surfaces, which reduces metallic adhesion and increases the tendency for surface film formation.

The objective of this investigation was to form ternary alloys of iron, cobalt, and silicon and to examine the influence of the silicon on friction and wear. In this investigation, additions of silicon were limited to its solubility range in the iron-cobalt alloy (5 weight percent). Friction and wear experiments were conducted with a hemispherical rider sliding on a rotating flat disk. Experiments were conducted in air, argon, and 0.25 percent stearic acid in hexadecane. Auger analysis was conducted during a vacuum sliding friction experiment in order to study segregation.

APPARATUS AND PROCEDURE

The apparatus used in this study to conduct friction and wear experiments is shown schematically in figure 1. The basic components of the apparatus are a 6.25-centimeter-diameter disk specimen 1.27 centimeters in thickness. It is contacted by a rider specimen with a 0.5-centimeter radius. The disk specimen is rotated by a variable-speed electric motor. Speed can be varied from 300 to 5250 centimeters per minute. The rider specimen is contained in an arm which has incorporated in it a strain-gage assembly for recording friction force. The rider is dead-weight loaded against the disk. Disk and rider materials were the same in each experiment. Where a liquid lubricant is used, a dish of the fluid is placed under the disk and rider, and the dish is filled until both specimens are under the fluid.

The apparatus is covered with a clear plastic box in which a positive argon pressure can be maintained. While the argon purge was not intended to exclude oxygen and water vapor totally, it was intended to minimize the concentration of these gases and to main-

tain a relatively constant environment from experiment to experiment.

Auger analysis to study surface segregation was conducted with a cylindrical mirror Auger analyzer which provides the capability of analyzing for all the elements present on the wear surface in less than 0.1 second. The apparatus used is described in detail in reference 5.

MATERIALS

The alloys used in this investigation were prepared from 99.95 percent iron, 99.94 percent cobalt (principal impurity nickel), and high-purity silicon. Equal parts of iron and cobalt were selected because this composition has the greatest degree of ordering as determined by X-ray analysis (ref. 2). The alloys were vacuum-induction-melted and poured into water-cooled copper molds. The as-cast structures were then machined into disk and rider specimens. Alloys were prepared containing 1, 2, 3, and 5 weight percent silicon with the balance of the alloy in each case being equal parts of iron and cobalt. The alloys were heat-treated in accordance with the procedure described in reference 2 in order to achieve the maximum ordering of the alloy.

Specimens from each casting were prepared for metallurgical examination. Both micrographs and hardness values were obtained for each alloy composition. A photomicrograph of the iron-cobalt alloy containing 5 percent silicon is presented in figure 2. An examination of figure 2 reveals a simple solid solution of the ternary alloy. The alloy is a single phase, as indicated by the phase diagram for this ternary system. Photomicrographs of the alloys containing less silicon were nearly the same as that shown in figure 2 with the exception of grain size. The presence of silicon in the alloy inhibited grain growth. With increasing amounts of silicon, grain size decreased. The overall reduction was, however, not marked.

Hardness measurements were made on each alloy and the results obtained are presented in figure 3. The hardness increased with increasing amounts of silicon. Even with 5 percent silicon, the alloy is relatively soft. The silicon did not produce brittleness. Plastic flow was readily observed around the hardness indenter. Increased hardness could be achieved by further additions of silicon and the precipitation of compounds such as tricobalt silicide (Co_3Si). Silicon concentrations in excess of 6 percent are sufficient to achieve this effect (ref. 5). The 440-C steel had a Rockwell C hardness of 60 (R_C-60).

EXPERIMENTAL RESULTS

Sliding friction experiments were conducted with an iron-cobalt alloy containing

various amounts of silicon. The friction and wear results obtained are presented in figure 4. The addition of silicon to the iron-cobalt alloy reduced both friction and wear from results obtained with the 50-percent-iron - 50-percent-cobalt alloy in the ordered state. Further, friction and wear decreased with increasing silicon content. A very marked reduction in both friction and wear occurred when the silicon content was increased from 3.0 to 5.0 percent. This reduction occurred even though both compositions were still solid solutions.

The experimental results of figure 4 were obtained in an argon environment. When similar experiments were conducted with the iron-cobalt-silicon alloys in air, higher friction coefficients resulted. In figure 5, friction coefficient for the iron - cobalt - 5-percent-silicon alloy is presented as a function of sliding velocity in both air and argon. At very low sliding velocity the friction coefficient in air was 0.6. With increased sliding speed, the friction coefficient decreased to a value of 0.45. Over the entire range of sliding velocities investigated, the friction coefficient in argon was less than in air.

In order to determine if the friction results obtained in figure 5 were the result of surface reaction films, an experiment was conducted with a change in environments. A friction coefficient was first measured in air for the iron - cobalt - 5-percent-silicon alloy sliding on itself. At a sliding velocity of 5 centimeters per second, the friction coefficient was 0.6. The plastic box covering the specimens was purged with argon after sliding in air was terminated. After a thorough purge, sliding with the same specimen was reinitiated. Friction coefficient is plotted as a function of time in figure 6 after sliding was commenced in the argon.

An examination of figure 6 indicates that once sliding was initiated in argon the initial friction coefficient was the same as that obtained in air. With repeated passes over the same surface (increased time), the friction coefficient decreased. After 12 minutes of sliding, the friction coefficient decreased to a value of 0.3. It did not decrease beyond this value. The results of figure 6 then indicate that the differences in friction coefficients in the two environments (air and argon) are a result of the nature of the surface films present.

Sliding friction experiments were conducted with the iron-cobalt-silicon alloys in a lubricating media, namely, 0.25 percent stearic acid in hexadecane. The object was to determine if the silicon afforded greater protection to the surface in the presence of an organic lubricant. The results obtained in these experiments are presented in figure 7. The coefficient of friction was essentially unaffected by silicon content. Wear, however, decreased with increasing amounts of silicon.

Comparative friction and wear experiments were conducted in argon for the iron - cobalt - 5-percent-silicon alloy with the ordered and disordered iron-cobalt alloy as well as with 440-C steel. The results of these experiments are presented in figure 8.

With the simple binary iron-cobalt alloy in the disordered state, both friction and wear were high; ordering appreciably reduced both, as was experienced in reference 2 in vacuum studies. The silicon addition, as evidenced by the data of figure 8, reduces friction and wear further.

Friction and wear data are presented in figure 8 for 440-C steel sliding on itself. This commonly used bearing steel exhibits markedly higher friction and wear than the ternary alloy sliding on itself. Wear is ten thousand times greater for the presently used 440-C bearing steel.

In order to compare more fully the friction and wear characteristics of the ternary alloy with 440C steel, experiments were conducted in both air and 0.25 percent stearic acid in hexadecane. The results obtained together with the data obtained in argon are presented in figure 9. The friction coefficient for the ternary alloy is higher in air than that obtained for 440-C steel. Wear, however, was a factor of 10 less than that observed with 440-C steel.

With the boundary lubricant, stearic acid, present both alloys in figure 9 exhibited the same coefficients of friction. Wear was slightly less for the ternary alloy.

Surface profile traces were obtained on the disk surfaces after each experiment, and two traces, one for the ternary alloy and the other for 440-C steel, are presented in figure 10. There was, as indicted by the traces, adhesive transfer to the 440-C steel disk in argon. This is evidenced in figure 10 by the peaks which rise above the disk baseline. In contrast, the trace for the ternary alloy exhibited very little if any surface disturbance.

DISCUSSION

The friction and wear data of this investigation indicate that alloys of iron and cobalt in the ordered state can be improved by the addition of small amounts of silicon. A simple ternary alloy exhibits sliding behavior superior to that for conventionally used bearing steels such as 440-C steel.

The binary iron-cobalt alloy does not provide the mechanical properties (i.e., hardness) needed for bearing applications. The alloy is a simple solid solution without a hardening phase. With the addition of silicon, cobalt compounds can be formed at sufficiently high concentrations of silicon and thereby provide for a second or hardening phase. In this study, the silicon content was deliberately kept in the solid solubility range. The objective was to show the effect of silicon on the friction and wear behavior in solid solution. It is well known that second or hardening phases will influence friction and wear (ref. 6). Hardnesses comparable to that obtained with bearing steels are achievable. Thus, even further reductions in friction and wear might be anticipated with the ternary alloys of this investigation when sufficient silicon is added to form a second

phase. Further, silicon extends the temperature range over which ordering in the iron-cobalt alloy can be maintained and thus provides for good friction and wear properties to higher temperatures.

It is fairly well understood how the second phase can influence friction and wear. The mechanism for the reduction of friction and wear by the alloying of elements in small concentrations in solid solution is, however, not understood. How can 5 percent of an alloying element added to a simple solid solution produce such a marked influence on friction and wear as was observed in this investigation with silicon? In order to answer this question, a sliding friction experiment was conducted with the 5-percent-silicon ternary alloy in vacuum. A cylindrical mirror Auger analyzer was used to study surface chemistry changes during sliding.

The vacuum friction experiment revealed that, under the same loading conditions used in this study and at the low sliding speed of 0.25 centimeter per second, silicon segregated to the alloy surface. With repeated passes over the same surface, the silicon concentration continued to increase. After 20 passes, the surface concentration of silicon remained essentially unchanged.

The segregation of the silicon to the alloy surface was essentially induced by the strain associated with the sliding friction process. Strain can produce sizable increases in the diffusion of alloying elements in a solvent metal in the solid state. Normally, such surface segregation occurs as a result of heating. The sliding conditions of the experiment (low speed and light load) minimize much of the heating effect.

The pronounced effect of small amounts of silicon in the iron-cobalt alloy on friction and wear can then be attributed to segregation of silicon to the alloy surface. Thus, surface concentrations may far exceed the quantity of alloying element (silicon) in the bulk. Earlier studies have shown that silicon will reduce the friction and wear of metals (refs. 4 and 7).

Silicon, on diffusion to and segregation at the alloy surface, can reduce metallic adhesion by reducing the amount of metal-to-metal contact that occurs across the interface. This results in a reduction of both friction and adhesive wear.

The very marked decrease in wear observed in figure 4 with the increase in silicon content from 3 to 5 percent indicates that it may be desirable to alloy to the solubility limit of the segregating element. The 5-percent alloy is at the solubility limit of silicon in the iron-cobalt alloy. Surface segregation near this limit may be enhanced. This may account for the difference in wear between the 3- and 5-percent-silicon-containing alloys.

In this investigation, the simple ternary alloy exhibited lower friction and wear than the frequently used bearing steel, 440-C steel, in an argon environment. The argon environment is not equivalent to a vacuum environment with respect to the elimination of environmental contaminants. It does, however, provide for the reduction of the effects of such environmental constituents as oxygen and water vapor on friction and wear.

Thus, it would appear from these studies that the ternary alloy system may offer considerable promise for those applications where the concentration of environmental contaminants which normally influence friction and wear is reduced (i.e., space applications).

SUMMARY OF RESULTS

The following results were obtained from an investigation of the influence of silicon on friction and wear of iron-cobalt alloys:

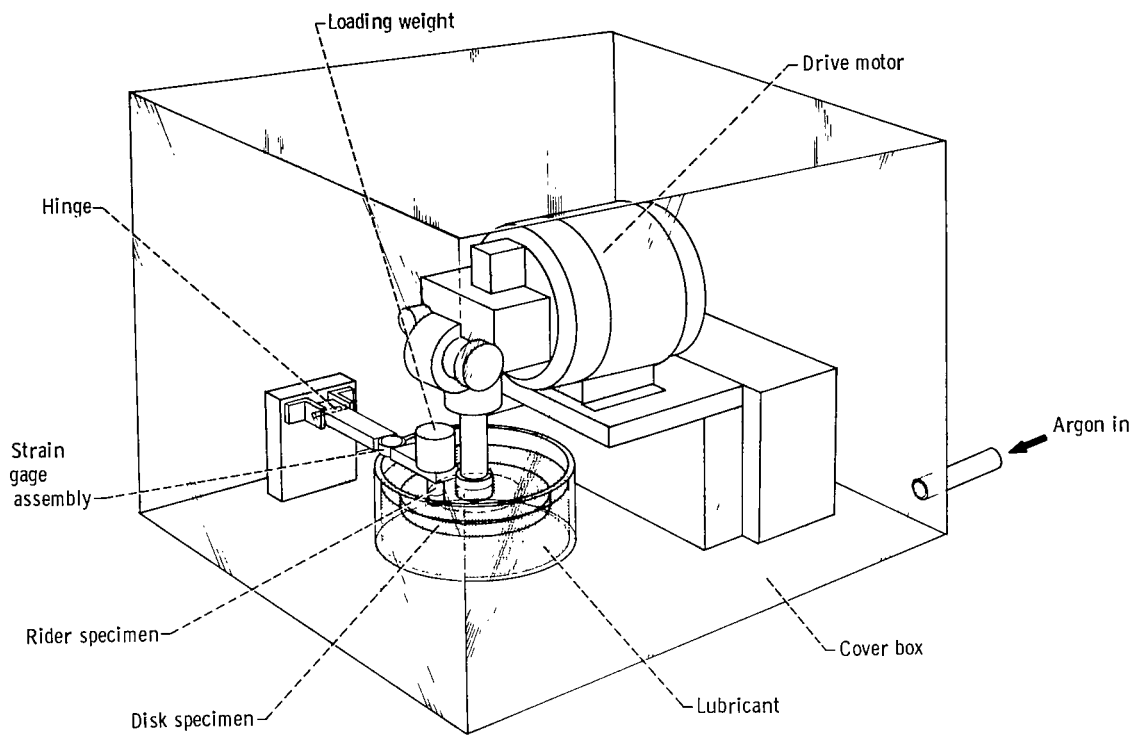
1. The addition of small amounts of silicon (5 percent and less) to a binary iron-cobalt alloy reduced the friction and wear of the simple binary alloy when sliding in argon.
2. A ternary iron - cobalt - 5-percent-silicon alloy exhibited lower wear in argon, air, and 0.25 percent stearic acid in hexadecane than 440-C steel. Friction for the ternary alloy in argon was also lower than observed with 440-C steel.
3. The ternary iron - cobalt - 5-percent-silicon alloy exhibited higher friction and wear in air than in argon and may offer promise in environments other than air.
4. During the sliding friction process, surface segregation of silicon to the ternary iron - cobalt - 5-percent-silicon alloy surface was observed. This increase in the surface concentration of silicon initiated by the sliding process may explain the pronounced effect of small amounts of bulk alloying elements on friction and wear.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 15, 1972,
114-03.

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Figure 1. - Friction apparatus.

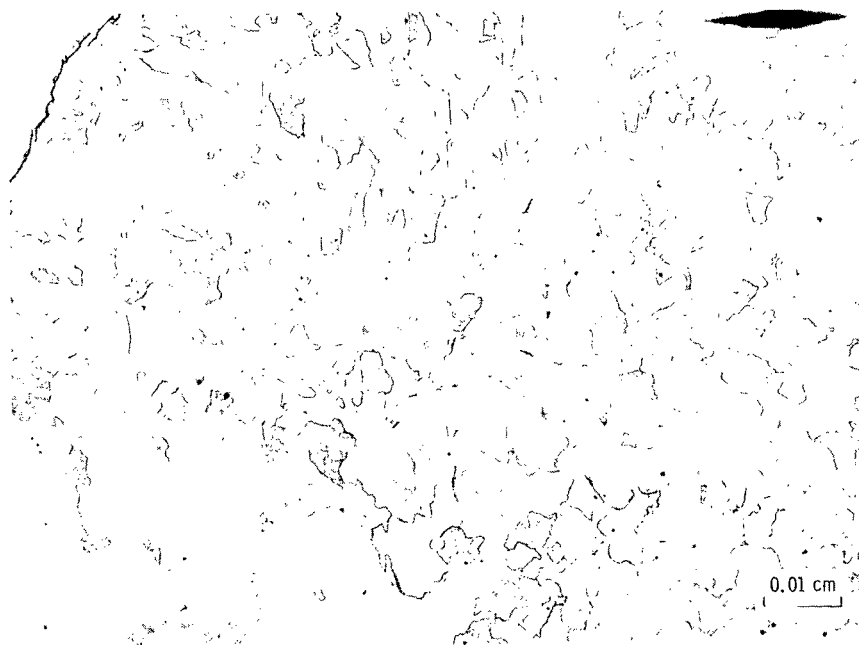


Figure 2. - Photomicrograph of iron - cobalt - 5-percent-silicon alloy. Nital etch.

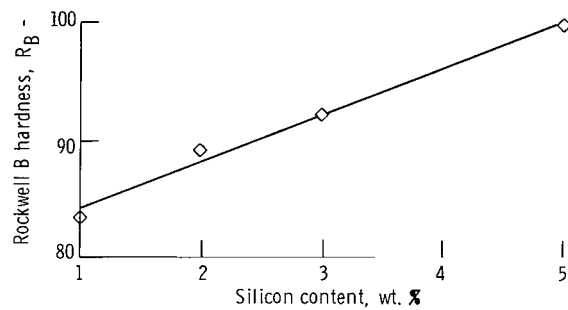


Figure 3. - Hardness of ordered iron-cobalt-silicon alloy as function of silicon content.

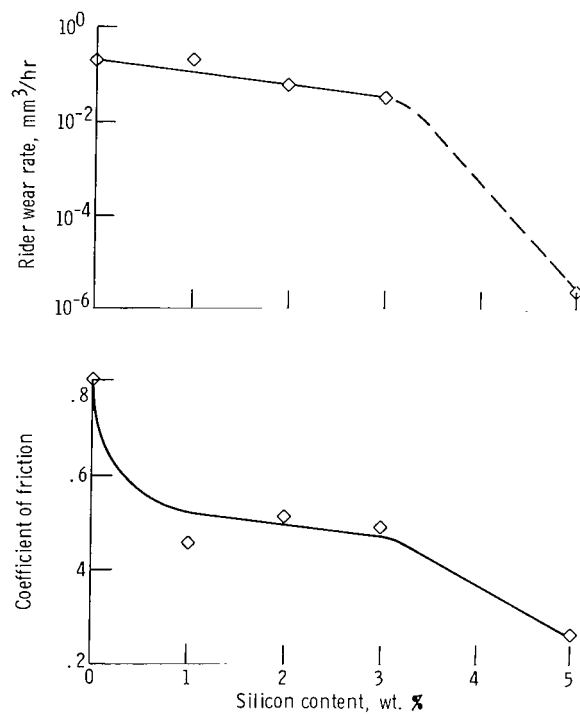


Figure 4. - Coefficient of friction and rider wear rate for iron-cobalt alloys containing various amounts of silicon when sliding in argon. Sliding velocity, 5 centimeters per second; load, 250 grams; temperature, 20°C .

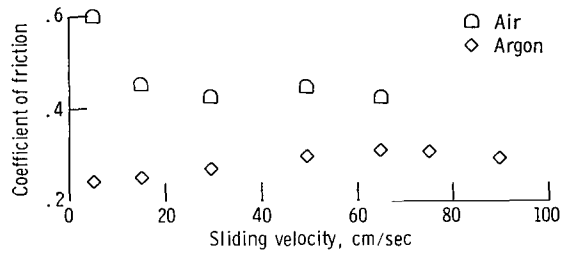


Figure 5. - Coefficient of friction at various sliding velocities for iron - cobalt - 5-percent silicon alloy sliding on itself in air and argon. Load, 250 grams; temperature, 20° C.

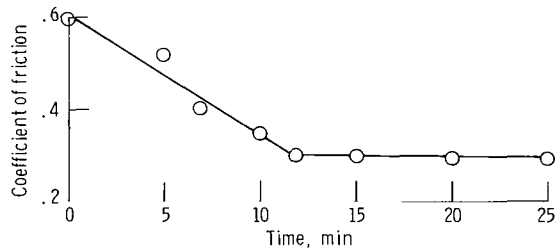


Figure 6. - Coefficient of friction of iron - cobalt - 5-percent silicon alloy in argon after sliding in air. Sliding velocity, 5 centimeters per second; load, 250 grams; temperature, 20° C.

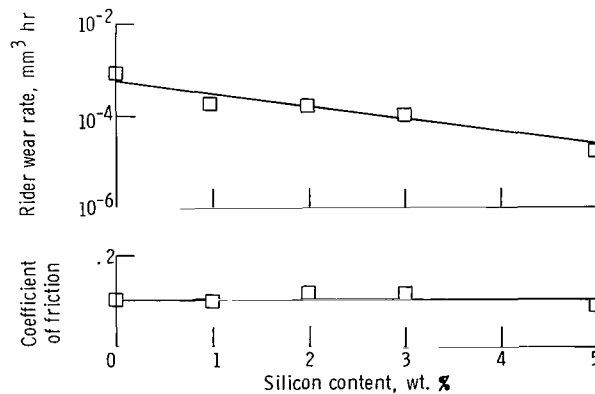


Figure 7. - Coefficient of friction and rider wear rate for iron-cobalt alloys containing various amounts of silicon when sliding in 0.25 percent stearic acid in hexadecane. Sliding velocity, 5 centimeters per second; load, 250 grams; temperature, 20° C.

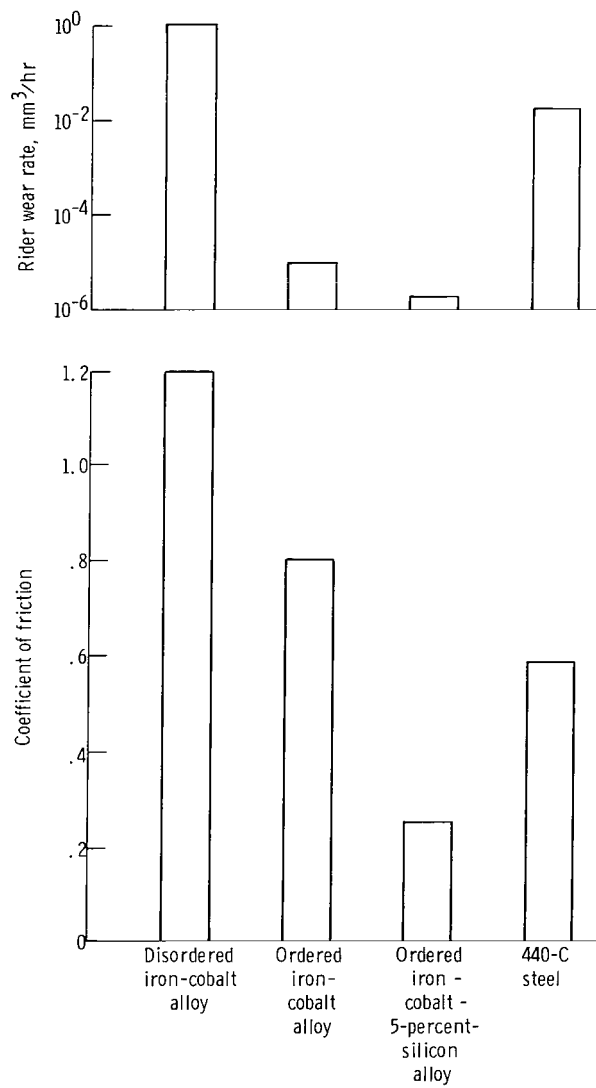


Figure 8. - Coefficient of friction and rider wear rate for various alloys sliding on themselves in argon. Sliding velocity, 5 centimeters per second; load, 250 grams; temperature, 20°C .

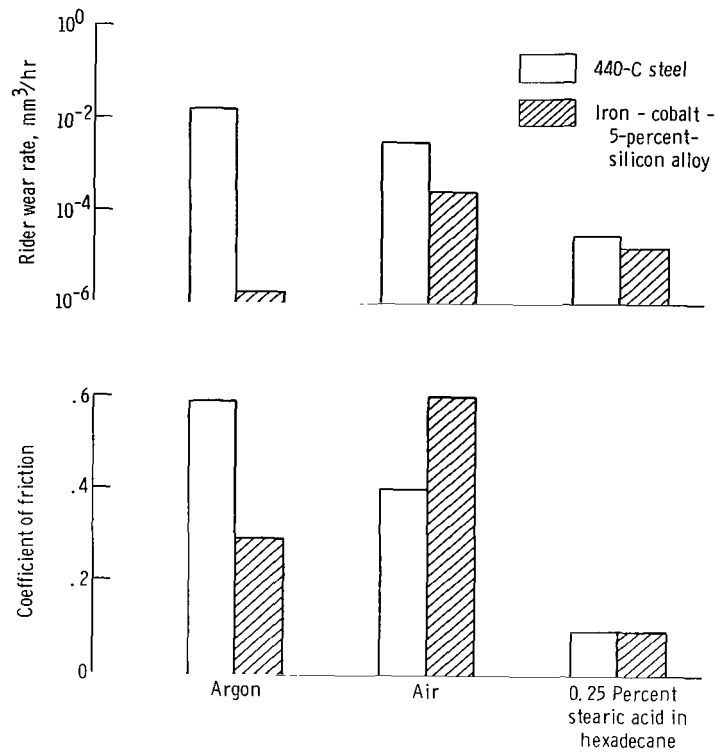
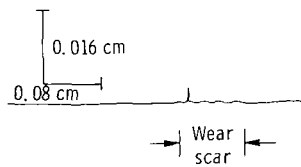
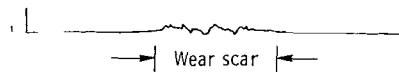


Figure 9. - Coefficient of friction and rider wear rate for two alloys sliding on themselves in three different environments. Sliding velocity, 5 centimeters per second; load, 250 grams; temperature, 20°C .



(a) Iron - cobalt - 5-percent-silicon alloy.



(b) 440-C steel.

Figure 10. - Surface profile traces of two disk surfaces after sliding in argon. Sliding velocity, 5 centimeters per second; load, 250 grams; temperature, 20°C .



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